High cloud properties from three years of MODIS Terra and Aqua Data over the Tropics

Gang Hong and Ping Yang

Department of Atmospheric Sciences, Texas A&M University, College Station, TX 77843, USA

Bo-Cai Gao

Remote Sensing Division, Naval Research Laboratory, Washington, DC 20375, USA

Bryan A. Baum

Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706, USA

Yong X. Hu

NASA Langley Research Center, Hampton, VA 23681, USA

Michael D. King and Steven Platnick

NASA Goddard Space Flight Center, Greenbelt, MD 20711, USA

Corresponding author address: Dr. Ping Yang, Department of Atmospheric Sciences, Texas A&M University, College Station, TX 77843; Tel: 979-845-4923.

Email: pyang@ariel.met.tamu.edu

Abstract

This study surveys the optical and microphysical properties of high (ice) clouds over the tropics (30°S–30°N) over a 3-year period from September 2002 through August 2005. The analyses are based on the gridded Level-3 cloud product (Collection 4) derived from the measurements acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard both the NASA Earth Observing System Terra and Aqua platforms. The cloud products provide daily, weekly, and monthly mean cloud fraction, cloud optical thickness, cloud effective particle size, cloud top temperature, cloud top pressure, and cloud effective emissivity (defined as cloud emittance multiplied by cloud fraction). The focus of this study is on high-level ice clouds. We classify the MODIS-derived high clouds as cirriform and deep convective clouds using the International Satellite Cloud Climatology Project (ISCCP) classification scheme. Cirriform clouds comprise more than 80% of the total high clouds, whereas deep convective clouds account for less than 20% of the total high clouds. High clouds are prevalent over the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), tropical Africa, Indian Ocean, and tropical and South America. Furthermore, land-ocean, morning-afternoon, and summer-winter variations of high cloud properties are also observed.

1. Introduction

High clouds occur frequently over the tropics (e.g., Liou 1986; Rossow and Schiffer 1999; Wylie et al. 1994; Liu et al. 1995; Wang et al. 1996, 1998; Wylie and Menzel 1999; Dessler and Yang 2003; Luo and Rossow 2004; Wylie et al., 2005; Stubenrauch et al., 2006). The effect of high clouds on the climate system is highly sensitive to their optical and microphysical properties (e.g., Stephens et al. 1990; Liu and Curry 1999; McFarquhar et al. 2002). Cloud parameterizations in climate models need to account properly for the temporal and spatial distributions of high cloud properties (Tselioudis and Jakob 2002; Ringer and Allan 2004; Lin and Zhang 2004; Li et al. 2005). The representation of tropical high clouds in general circulation models (GCMs) has been evaluated (Lin and Zhang 2004; Zhang et al. 2005; Li et al. 2005). Zhang et al. (2005) compared basic cloud climatologies from ten GCMs with satellite measurements from the International Satellite Cloud Climatology Project (ISCCP, Schiffer and Rossow 1983; Rossow and Schiffer 1991, 1999) and the Clouds and Earth's Radiant Energy System (CERES, Wielicki et al. 1996) missions. Significant differences between the model simulations and measurements were found.

This study is intended to investigate the characteristics of high clouds on the basis of the cloud products derived from the measurements acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (Barnes et al. 1998) on NASA's Earth Observing System (EOS) Terra and Aqua platforms over a three-year period. The MODIS sensors provide unique capabilities to investigate cloud properties from space observations. In addition to cloud fraction, cloud top temperature, cloud top pressure, and effective cloud amount, MODIS also provides information about thermodynamic cloud phase, optical thickness, and effective particle size. The optical thickness and effective particle size are used to estimate ice water path, a parameter of interest to forecasters and climate modelers.

Stephens et al. (1990) investigated the relevance of the microphysical and radiative properties of cirrus clouds to climate and climatic feedback. It was found that the influence of cirrus clouds on climate was affected strongly by the values of effective particle size and asymmetry parameter. Effective particle size has been suggested to be a function of ice water content and/or cloud temperature (McFarlane et al. 1992; Ou and Liou 1995; Wyser 1998). The effect of ice cloud feedback on GCM simulations can be either positive or negative, depending on the value of effective particle size assumed. Pilewskie and Valero (1996), Chung et al. (2000), and Wendish et al. (2005) also found that ice cloud forcing is sensitive to ice effective particle size and optical thickness.

Other cloud climatologies are available but do not provide a complete set of cloud properties. For example, Wylie et al. (2005) investigate the frequency, geographical distribution, and temporal variations of upper tropospheric clouds using 22 years (from 1979 to 2001) of NOAA polar-orbiting High-Resolution Infrared Radiometer Sounder (HIRS/2) multispectral data. The HIRS/2 has a nominal field of view (FOV) of approximately 17 km at nadir. The HIRS/2 cirrus climatology reports on the geographical and seasonal distributions of cloud fraction, cloud top pressure, and effective cloud amount (cloud fraction N multiplied by cloud emittance ε). While clouds were found in 75% of the data, high clouds (cloud top pressure $P_c < 440$ hPa) were found in 33% of the cloud cases. Furthermore, 15%, 15%, and 3% of these high clouds were transmissive ($N\varepsilon < 0.5$), thick ($0.5 < N\varepsilon < 0.95$), and opaque ($N\varepsilon > 0.95$), respectively.

The ISCCP has produced over twenty years of cloud products with a spatial resolution of 20 km and a temporal resolution of 3 hours (Schiffer and Rossow 1983; Rossow and Schiffer 1991, 1999). The ISCCP products contain various cloud optical and microphysical parameters, including cloud fraction, top temperature, top pressure, optical thickness, and water path, available from the ISCCP C-series and D-series (Rossow and Schiffer 1999). However, the information about cloud effective particle size is quite limited because there is one particle size assumed for water clouds and another for ice clouds. Specifically, water clouds are assumed to be composed of liquid water droplets (spheres) with an effective radius of 10 μm, while ice clouds are composed solely of fractal polycrystals with an effective radius of 30 μm. A cloud is assumed to be an ice cloud when the cloud top temperature is less than 260 K. According to the ISCCP cloud products, high clouds cover approximately 22% of the globe and 24% of the tropics.

Stubenrauch et al. (2006) analyze eight years (1987–1995) of the TIROS-N Observational Vertical Sounder (TOVS) Pathfinder B (hereafter, referred as TOVS Path-B) data from NOAA polar orbiting satellites. The TOVS Path-B analyses indicate that cirrus clouds cover approximately 27% of the globe and 45% of the tropics. These results are similar to those of Wylie et al. (2005). The frequency of high clouds derived by Stubenrauch et al. (2006) and Wylie et al. (2005) is larger than that from ISCCP.

There are currently two MODIS imagers in operation, one each on the Terra and Aqua platforms. The EOS Terra platform was launched in December 1999, while the Aqua platform was launched in May 2002. MODIS measures radiances in 36 spectral bands at wavelengths from 0.4 to 14.2 μm and has a swath width of 2330 km. The spatial resolution at nadir ranges from 250 m to 1 km depending on the wavelength. MODIS has a repeat cycle of 16 days, and global coverage can be obtained in approximately 2 days. The coverage of key atmospheric bands by the MODIS instruments largely enhances the capability of remote sensing of high clouds from space-borne observations (King et al. 2003; Platnick et al. 2003). In terms of the retrieval of the ice cloud optical thickness and effective particle size retrievals, the Collection 4 MODIS cloud products are based on the ice cloud optical models (Baum et al. 2000; King et al. 2004) that account for a mixture of various ice habits whose single-scattering properties are computed from the methods reported by Yang and Liou (1996a, b). Recently new ice cloud bulk scattering models (Baum et al. 2005a, b) have been developed and are being used operationally for the Collection 5 MODIS cloud products. However, as only Collection 4 is available currently, our study is based on Collection 4 products.

Based on the three years of the MODIS cloud products, we investigate high cloud properties over the tropics (30°S–30°N). Section 2 briefly describes the MODIS high cloud products and the classification of cirriform and deep convective clouds. Three-year mean properties and monthly variations of high clouds are analyzed in Section 3.1. Geographical distributions and seasonal variation of high clouds are analyzed in Sections 3.2 and 3.3, respectively. In Section 3.4, we investigate the zonal means of high cloud properties with the latitudes. Section 4 summarizes this study.

2. Data and methodology

The daily MODIS Level-3 atmosphere products (MOD08_D3 and MYD08_D3) from the Terra and Aqua measurements contain roughly 600 statistical datasets (King et al. 2003). The Level-3 products are derived from four Level-2 atmosphere products including aerosol properties (MOD04), perceptible water (MOD05), cloud properties (MOD06), and atmospheric profiles (MOD07). The MOD08_D3 (MYD08_D3) products are aggregated with a $1° \times 1°$ (longitude and latitude) spatial resolution over the globe. Three years of the daily MOD08_D3 and MYD08_D3 data from September 2002 to August 2005 over the tropics (between 30°S and 30°N) are used in the present analysis.

The simple statistics of the mean or QA-weighted mean of high cloud properties within each grid cell is available from the MOD08_D3 (MYD08_D3) products. Cloud fraction can be derived from the ratio of the counts flagged as cloudy to the total observations within each grid cell. The high cloud optical thickness and effective particle size derived from the MODIS visible and near-infrared channel radiances are taken directly from the QA-weighted means in the MOD08_D3 (MYD08_D3) products. Additionally, cloud top pressure, top temperature, and effective emissivity are provided in the MOD08_D3 (MYD08_D3) products.

We also study the properties of cirriform and deep convective clouds. The ISCCP cloud classification (Rossow and Schiffer 1999) classifies a high cloud (ice cloud) if the cloud top pressure is less than 440 hPa as a cirrus, cirrostratus, or deep convective cloud. A cirrus cloud is defined as a high cloud with an optical thickness (τ) less than 3.6. A cirrostratus cloud is defined as a high cloud with $3.6 < \tau < 23.0$. A deep convective cloud is defined as a high cloud with $\tau > 23.0$. We use the ISCCP classification (cirrus, cirrostratus, and deep convective clouds) to subdivide the results provided in the MOD08_D3 (MYD08_D3) products. However, we use two classes for high clouds, one for cirriform clouds including cirrus and cirrostratus clouds (Rao et al. 1990; Chou and Neelin 1999; Cartalis et al. 2004), and the other for deep convective clouds.

3. Results

3.1 Average high cloud properties

The three-year mean properties of all high clouds as well as the subgroups of cirriform and deep convective clouds are listed in Table 1. The high cloud properties over ocean and land from Terra (10:30 AM) and Aqua (13:30 PM) are provided separately. Based on these statistics, we investigate potential differences between the results over land and ocean as well as the diurnal variations of cloud properties.

For all high clouds, the means of high cloud fraction, cloud top pressure, cloud top temperature, optical thickness, effective particle size, and effective emissivity are 22.7%, 280 hPa, 231 K, 12.8, 26.5 μm, 0.69, respectively. Some general features are noted for all high clouds. First, the total high cloud fraction is higher over land than ocean for both morning (Terra) and afternoon (Aqua). However, high cloud fraction tends to increase from morning to afternoon. Cloud top pressure and cloud top temperature have higher values over land than ocean for both Terra and Aqua. In contrast, high cloud effective particle size and effective emissivity have larger values over ocean. Cloud optical thickness and particle size display both land-ocean and morning-afternoon differences. Both optical thickness and effective particle size have larger values in the morning over ocean while the largest values occur over land in the afternoon. These features in the data are consistent with the fact that high clouds tend to develop in the early afternoon.

The mean value of the total high cloud fraction (22.7%) from both MODIS Terra and Aqua platforms is in agreement with that determined from the ISCCP data (Rossow and Shiffer 1999), which has a mean value of high cloud fraction in daytime over the tropics of 23.8%. However, it must be noted that the time coverage of ISCCP and MODIS is not the same. The underestimation of high cloud fraction by the MODIS with respect to the ISCCP is only about 1%. This is mostly due to different thresholds of detectable thin cirrus cloud (Jin et al. 1996; Wylie and Wang 1997; Rossow and Schiffer 1999; Stubenrauch et al. 1999). Zhang et al. (2005) found that the different minimum detectable thresholds of cloud optical thickness could lead to large differences in cloud fraction. Of the total high cloud fraction, the primary contribution is from the cirriform cloud class, which contributes over 80% of the total high cloud fraction. This is consistent with the ISCCP results, which found that high clouds are mainly cirrus clouds. The deep convective cloud fraction (3.8) from the MODIS is close to that derived from the ISCCP (2.7) (Rossow and Shiffer 1999).

Cirriform clouds have higher values of cloud fraction, top pressure, top temperature, optical thickness, and effective emissivity over land than over ocean, whereas they have larger effective particle size and effective emissivity over ocean. One interesting feature is that the differences between the cirriform cloud fraction over land and ocean in the morning are approximately twice of those in the afternoon. The cirriform cloud fraction over land tends to decrease slightly from morning (24.5) to afternoon (23.3), while the cirriform cloud fraction over ocean increases from 15.9 to 18.7.

Deep convective clouds have higher values of cloud fraction, top pressure, top temperature, and optical thickness over land than over ocean in both the morning and afternoon. Deep convective cloud effective particle size and effective emissivity are in contrast. The deep convective cloud fraction over land increases by almost a factor of 1.5

from morning to afternoon. Over ocean, the deep convective cloud fraction has its maximum in the morning and decreases slightly from morning to afternoon. The morning-afternoon and land-ocean contrasts are in agreement with those reported in studies of satellite precipitation radar and infrared sensor data (Alcala and Dessler 2002; Hong et al. 2006).

Figures 1-3 show the frequency distributions of cloud top temperature, effective emissivity, optical thickness, and effective particle size for all high clouds as well as the cirriform and deep convective cloud classes over ocean and land for the tropics (30°S–30°N) from Terra and Aqua. The histograms of the high cloud top temperatures are flat in the range of 220–240 K (Figure 1a). The land-ocean contrast of the distributions in the afternoon is pronounced. The maximum frequency of high cloud top temperature over land occurs at about 235 K while that over ocean occurs at about 222 K. The histogram of high cloud effective emissivities (Figure 1b) has a maximum at about 0.92 in the afternoon. The land-ocean contrast of the frequency distribution of high cloud effective emissivities in the morning is pronounced. The maximum frequency of high cloud effective emissivity over land occurs at about 0.68 whereas that over ocean occurs at approximately 0.88. High cloud optical thickness peaks at approximately between 2 and 3 (Figure 1c). This indicates that most high clouds are optically thin. The peak in the frequencies of total high cloud optical thickness occurs at a larger optical thickness over land than over ocean. The peak in high cloud effective particle size peaks at about 29 μm over ocean but at slightly smaller values over land (Figure 1d). The frequency distributions over ocean are much narrower than those over land. The frequency distributions of cirriform cloud top temperature, optical thickness, and effective particle size (Figures 2a, c, and d) have similar features as those for total high clouds. Cirriform cloud effective emissivities have their maximum frequencies at larger values over ocean then those over land (Figure 2b). The frequency distributions in the afternoon have a pronounced land-ocean contrast.

The maximum frequencies of deep convective cloud top temperatures (Figure 3a) over land appear at about 202 K in the morning and about 220 K in the afternoon, whereas those over ocean appear at about 202 K in the morning and about 208 K in the afternoon. Moreover, the frequencies have narrower distributions in the morning. Deep convective cloud effective emissivities (Figure 3b) have a peak in the frequency distribution at 0.88 in the morning and 0.94 in the afternoon. The land-ocean contrast in the deep convective cloud effective emissivities is more pronounced in the afternoon. Deep convective cloud optical thicknesses (Figure 3c) have a peak in frequency at a value of approximately 23, which is the lowest threshold value used to identify deep convective clouds. Similar to total high clouds (Figure 1d) and cirriform clouds (Figure 2d), deep convective clouds (Figure 3d) have sharper land-ocean contrasts in their frequency distributions. All deep convective clouds have their maximum frequencies at 27–28 μm. But the deep convective clouds over land in the morning have a distinct feature, a secondary peak of their frequency distribution at around 13 μm.

Figure 4 shows the monthly variation of the high cloud fraction, effective emissivity, optical thickness, and effective particle size for the three-year period from Terra and Aqua over the tropics. In general, the monthly variations over the same underlying surface (ocean or land) from Terra and Aqua have similar changes with months. No obvious trends are observed in the monthly variations for the three years. The high cloud fraction does show seasonal variations that are consistent with the high cloud survey based on eight years of HIRS data (Wylie and Menzel 1999). The high cloud effective emissivities and optical thicknesses (Figures 4b and c) also have distinct seasonal variations over land. The high cloud effective particle sizes (Figure 4d) display very weak variations. The land-ocean and morning-afternoon contrasts are also evident but are essentially consistent with those in Table 1.

3.2. Geographical high cloud distributions

Figure 5 shows the geographical distribution of the three-year mean fractions for total high cloud, cirriform, and deep convective clouds from Terra and Aqua over the tropics. The distribution of these three cloud groups in the morning (left panels) are the same as those in the afternoon (right panels). The major concentrations of high clouds occur over the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), tropical Africa, Indian Ocean, and tropical and South America. These geographical distributions agree well with many previous studies (e.g., Wylie et al. 1994; Wylie and Menzel 1999; Alcala and Dessler 2002; Jiang et al. 2004; Luo and Rossow 2004; Tian et al. 2004; Wylie et al., 2005; Hong et al. 2005, 2006; Stubenrauch et al., 2006). Additionally, the distribution of cirriform and deep convective clouds reveals that cirriform clouds tend to occur in conjunction with tropical deep convective systems.

From morning (Figure 5, left panels) to afternoon (Figure 5, right panels), total high cloud fractions generally increase over both land and ocean. However, cirriform cloud fractions generally increase over ocean and decrease over land. In contrast to the case for cirriform clouds, deep convective cloud fractions generally decrease over ocean and increase over land. These morning-afternoon variations in cloud fraction are consistent with the corresponding features of their three-year means in Table 1. From morning to afternoon over ocean, the increase of cirriform clouds occur in conjunction with a decrease in deep convective clouds. This indicates that cirriform clouds develop in conjunction with the dissipation of tropical deep convective clouds over ocean. From morning to afternoon over land, the heating of land surface enhances the instability of atmosphere (Jin and Dickinson 2000), and leads to the development of deep convective clouds. Cirriform clouds over land associated with deep convective clouds decrease slightly from morning to afternoon. Over the Indonesian maritime region, cirriform clouds occur frequently over maritime continents in the morning. Deep convective clouds over this region display a larger land-ocean contrast in the morning than in the afternoon.

Figures 6 and 7 show the geographical distribution of three-year means of high cloud optical thickness, effective particle size, effective emissivity, and cloud top temperature from Terra and Aqua, respectively. The geographical distributions from Terra are similar to those from Aqua. The morning-afternoon contrasts of high cloud optical thickness, effective particle size, and top temperature are evident and are generally consistent with those of the three-year means over the entire tropics presented in Table 1. High cloud optical thickness (Figures 6a and 7a) and effective particle size (Figures 6b and 7b) have pronounced land-ocean contrasts. The land-ocean contrast of high cloud optical thickness increases from morning (Figure 6a) to afternoon (Figure 7a). However, the land-ocean contrast of high cloud effective particle size decreases from morning to afternoon. Those distinct land-ocean contrasts are also consistent with the results listed in Table 1. High cloud effective emissivity (Figures 6c and 7c) and cloud top temperature (Figures 6d and 7d) essentially increase from the equator to higher latitudes.

3.3. Seasonal high cloud distributions

Figure 8 shows the seasonal distributions of the Terra and Aqua MODIS high cloud fraction, optical thickness, and effective particle size in the northern hemisphere summer and winter seasons. The months of June, July, and August (JJA) are denoted as summer in the northern hemisphere and the months of December, January, and February (DJF) are denoted as winter in the northern hemisphere. The seasonal high cloud optical thicknesses (Figures 8c and d) and effective particle sizes (Figures 8e and f) are averaged over the regions where the high cloud fractions are above 0.5%. The white regions in these figures denote areas in which the high cloud fractions are less than 0.5%. As expected, the ITCZ is denoted by high cloud fractions (Figures 8a and b), and moves south with the sun from summer to winter. This is in agreement with many previous studies (e.g., Wylie et al. 1994; Jin et al. 1996; Wylie and Menzel 1999; Tian et al. 2004; Wylie et al., 2005; Hong et al. 2005; Stubenrauch et al., 2006). High cloud optical thicknesses (Figures 8c and d) do not show the distinct seasonal variation as high cloud fractions. In winter, the highest values of optical thickness appear over Southeast Asia. High cloud optical thicknesses tend to be large along the Andes Mountains in both summer and winter. Over Africa and the tropical Atlantic, the high values of cloud optical thickness tend to shift south from summer to winter. High cloud effective particle sizes (Figures 8e and f) generally have a southern shift from summer to winter. The land-ocean contrasts of cloud effective particle sizes are very pronounced. Moreover, the largest cloud effective particle sizes are over ocean away from the coasts in the northern hemisphere in summer. However, in winter, the largest cloud effective particle sizes are located over the coasts in the northern hemisphere.

To study the seasonal cycle in more detail, the monthly means of cloud fraction, optical thickness, effective particle size, cloud top temperature, and effective emissivity of high cloud and cirriform and deep convective clouds from the Terra and Aqua over the tropical land and ocean have been averaged over the three-year period and are shown in Figure 9. The morning-afternoon and land-ocean contrasts of these monthly cloud properties agree well with those of the three-year mean properties found in Table 1.

The cloud fractions of the total and cirriform high clouds (Figures 9a and b) have stronger seasonal variations over land than over ocean. The deep convective cloud fractions (Figure 9c) have stronger seasonal variations in the afternoon than in the morning. The monthly cloud fractions of the total and cirriform high clouds in the afternoon are similar to those in the morning. Over both land and ocean, the seasonal variations of cloud fractions of the total and cirriform high clouds are generally with minima in northern hemisphere summer and with maxima in winter or spring. Deep convective clouds form less frequently in February or March over ocean, but more frequently in June or November. Over land, the monthly variation of deep convective clouds is more pronounced in the afternoon than in the morning. There are pronounced secondary maxima for cloud fractions over ocean in spring or fall.

The optical thicknesses of total high and cirriform clouds (Figures 9d and e) have stronger seasonal variations over land than over ocean. In general, monthly variations of optical thicknesses have similar trends in the morning and afternoon over the same underlying surface type although the months associated with minima and maxima of cloud optical thicknesses vary over ocean and land in the morning or afternoon. The seasonal variations of cloud effective sizes are very weak and vary in the range of about 2 μm (Figures 9f–i). Cloud top temperatures (Figures 9j–l) vary in the range of about 5 K. Cloud effective emissivities (Figures 9m–o) generally have stronger seasonal variations over land. Over ocean, they have slightly stronger seasonal variations in the afternoon. Over land, high clouds and cirriform clouds have their maxima in summer and minima of the effective emissivities in winter. The effective emissivities of deep convective clouds have pronounced seasonal variations only over land in the morning and over ocean in the afternoon.

3.4. Zonal means of high cloud properties

The zonal means of cloud fraction, optical thickness, and effective particle size for tropical total high cloud as well as cirriform and deep convective cloud as a function of latitude are shown in Figure 10. The zonal means are shown separately over land and ocean from Terra and Aqua for northern hemisphere summer and winter to investigate the land-ocean contrast and seasonal variations.

Figure 10a shows the distribution of high cloud properties with latitude. In summer, the peak in high cloud fraction occurs between 8–10°N and the lowest values are around 18°S. Additionally, the latitudes corresponding to the highest and lowest cloud fractions over land in the same seasons differ from those over ocean by a few degrees. The high cloud fractions in winter have a unique feature indicating of distinct double peaks between 15°S and 15°N over land and between 10°S and 10°N over ocean.

The variation of high cloud fractions with latitude are larger over ocean in summer than over land, but in winter the situation is reversed. The seasonal shifting of high cloud optical thicknesses (Figure 10b) is not as regular as that of high cloud fractions. Over land, the maxima of the high cloud optical thicknesses located at about 28°N in summer and 30°S in winter. Over ocean, the high cloud optical thicknesses have their maximum at 22°S in summer and 30°N in winter. High cloud optical thicknesses show stronger variation with latitude over land, as well as high cloud effective particle sizes (Figure 10c). Large values of high cloud effective particle sizes over land are near the equator and extend to higher latitudes in the southern hemisphere. High cloud effective particle sizes over ocean in winter weakly depend on the latitudes, whereas those over ocean during the summer have their largest values near the equator. The minima of high cloud effective particle sizes occurs at about 15°N over land in both the morning and afternoon, 18°S over ocean in the morning, and 30°N over ocean in the afternoon.

Cirriform cloud fractions (Figure 10d) have similar distributions as the total high cloud. Over land from summer to winter, the peaks of cirriform cloud optical thicknesses (Figure 10e) shift from 30°N to 10°S, as well as their minima shift from 12°S to 12°N. The variation of cirriform cloud optical thickness over land is much stronger than over ocean in both summer and winter. The distributions of cirriform cloud effective particle sizes (Figure 10f) are similar to those for high clouds.

The distribution of deep convective clouds (Figure 10g) is similar to those for total high clouds and cirriform clouds except over land in summer, which have a peak at 30°N. The deep convective cloud fractions over ocean in summer also have a slightly secondary peak around 6°S. Over land, the deep convective cloud fractions vary more with latitude in winter than in summer. However, the deep convective cloud fractions over ocean vary less with latitude in winter than in summer. The influence of midlatitude storm belts on the deep convective cloud fraction is evident. At high latitudes (30°S and 30°N), the deep convective cloud fractions tend to be larger. The deep convective cloud optical thicknesses (Figure 10h) are higher over land in both summer and winter. Over ocean, the deep convective cloud optical thicknesses tend to decrease from 30°S to 30°N in summer and decrease from 30°S to 30°N in winter. The deep convective cloud optical thicknesses over land in summer peak at 30°S and also have a pronounced local peak at 13°N. The deep convective cloud optical thicknesses over land in winter have their minimum around 13°N. The deep convective cloud effective particle sizes (Figure 10i) show more latitudinal variation over land than over ocean in both summer and winter. However, their summer-winter contrasts are quite pronounced. In summer, the effective particle sizes over land are at a minimum at about 12°S. The largest values occur near the equator and extend to the higher latitudes in the northern hemisphere. In contrast, the effective particle sizes over land in winter have minimal values at about 15°N, and the highest values occur near the equator and extend to the higher latitudes in the southern hemisphere. Similar features of the summer-winter contrast are also seen for the effective particle sizes for deep convective clouds over ocean in summer and winter.

4. Summary

The MODIS measurements from the Terra and Aqua platforms provide an unpredicted opportunity to study the climatology of high cloud properties. Three years (September 2002 through August 2005) of the MODIS Collection 4 cloud products are analyzed with a focus on high (ice) clouds. The cloud properties include cloud fraction, cloud optical thickness, effective particle size, cloud top temperature, cloud top pressure, and effective emissivity. We investigate the characteristics of all high ice clouds over the tropics (30°S–30°N) as well as subclasses designated as cirriform and deep convective clouds based on the ISCCP classification approach.

The three-year mean properties of high clouds are discussed over ocean and land in the morning (Terra) and afternoon (Aqua). The land-ocean and morning-afternoon contrasts are pronounced for cloud properties of all high clouds as well as cirriform and deep convective clouds. A major portion (over 80%) of all high clouds are cirriform clouds. The frequency (histogram) distributions of cloud top temperature, effective emissivity, optical thickness, and effective particle size for high clouds and cirriform and deep convective clouds are investigated over ocean and land from Terra and Aqua separately. Seasonal variations are found for high cloud properties from the monthly variations of the three years of data. The seasonal variation of all high cloud properties show pronounced morning-afternoon and land-ocean contrasts.

The geographical distribution of cloud fractions of all high clouds as well as cirriform and deep convective clouds have similar patterns. High clouds are concentrated over the ITCZ, SPCZ, tropical Africa, Indian Ocean, and tropical and South America. Over ocean, cirriform clouds develop in association with the dissipation of tropical deep convective clouds from morning to afternoon. However, over land the cirriform clouds decrease slightly with the development of deep convective clouds,. The geographical distribution of high cloud properties from Terra are similar to those from Aqua. The highest values of high cloud optical thickness occur over land while the largest effective particle sizes occur over ocean. The effective emissivities and cloud top temperatures for high clouds tend to increase from the equator toward higher latitudes.

The analyses of morning-afternoon contrasts in cirriform cloud fractions introduce a new way of studying the controversial cirrus "iris effect" (Lindzen et al. 2001; Lin et al. 2002). From the iris effect theory, cirrus clouds cause strong negative feedbacks in the climate system and tend to decrease the surface temperature when the increase of CO_2 warms the surface. The cirrus iris effect is based on the assumption that when CO_2 traps more heat in the atmosphere, the surface temperature should increase, leading to increases in the lapse rate that, in turn, enhances convection. As a result, the convection cycle becomes more efficient and thereby reduces cirrus clouds and water vapor in the upper troposphere. This will reduce the greenhouse warming effect from the cirrus and water vapor in the upper atmosphere and cool the surface. While the morning-afternoon contrast over land supports this assumption, it is not so in the case of the morning-afternoon contrast over ocean. It is possible that the feedback over ocean could be either very weak or even have a different sign.

High cloud fraction has a distinct seasonal shifting south from the northern hemisphere from boreal summer to winter. The geographical distributions of the optical thicknesses and effective particle sizes of these clouds also show seasonal variations. The land-ocean and summer-winter contrasts are also found in the zonal means of the various cloud properties.

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TABLE 1. The three-year mean properties of high cloud and cirriform and deep convective clouds from September 2002 to August 2005 over the tropics (30°S–30°N). All properties are based on daytime results from the MODIS aboard Terra and Aqua at the local equatorial crossing times of 10:30 and 13:30, respectively.

Cloud Properties	Terra			Aqua			Terra and Aqua		
	Land	Ocean	Total	Land	Ocean	Total	Land	Ocean	Total
High Cloud									
Fraction (%)	28.8	19.5	21.7	29.3	21.7	23.6	29.1	20.6	22.7
Top pressure (hPa)	298.2	279.9	285.7	286.1	268.6	274.0	292.2	274.3	279.9
Top temperature (K)	234.4	229.9	231.3	232.3	228.7	229.8	233.4	229.3	230.6
Optical thickness	12.7	13.3	13.1	14.7	11.4	12.4	13.7	12.4	12.8
Effective radius (μm)	23.0	28.0	26.4	24.0	27.6	26.5	23.5	27.8	26.5
Effective emissivity	0.66	0.71	0.70	0.65	0.69	0.68	0.66	0.70	0.69
Cirriform Cloud									
Fraction (%)	24.5	15.9	18.0	23.3	18.7	19.9	23.9	17.3	19.0
Top pressure (hPa)	306.0	296.1	299.3	291.8	277.2	281.4	298.9	286.7	290.4
Top temperature (K)	235.5	232.7	233.6	233.3	230.1	231.0	234.4	231.4	232.3
Optical thickness	7.9	7.5	7.6	8.2	7.5	7.7	8.1	7.5	7.7
Effective radius (μm)	22.8	27.9	26.3	23.8	27.6	26.5	23.3	27.8	26.4
Effective emissivity	0.63	0.68	0.66	0.60	0.65	0.64	0.62	0.67	0.65
Deep Convective Cloud									
Fraction (%)	4.3	3.6	3.8	6.0	3.0	3.7	5.2	3.3	3.8
Top pressure (hPa)	254.2	208.8	221.3	264.3	215.1	234.9	259.3	212.0	228.1
Top temperature (K)	227.8	217.5	220.3	228.4	219.9	223.3	228.1	218.7	221.8
Optical thickness	39.9	38.7	39.1	39.9	35.9	37.5	39.9	37.3	38.3
Effective radius (μm)	24.2	28.0	27.0	24.9	27.5	26.4	24.6	27.8	26.7
Effective emissivity	0.84	0.89	0.87	0.86	0.92	0.90	0.85	0.91	0.89

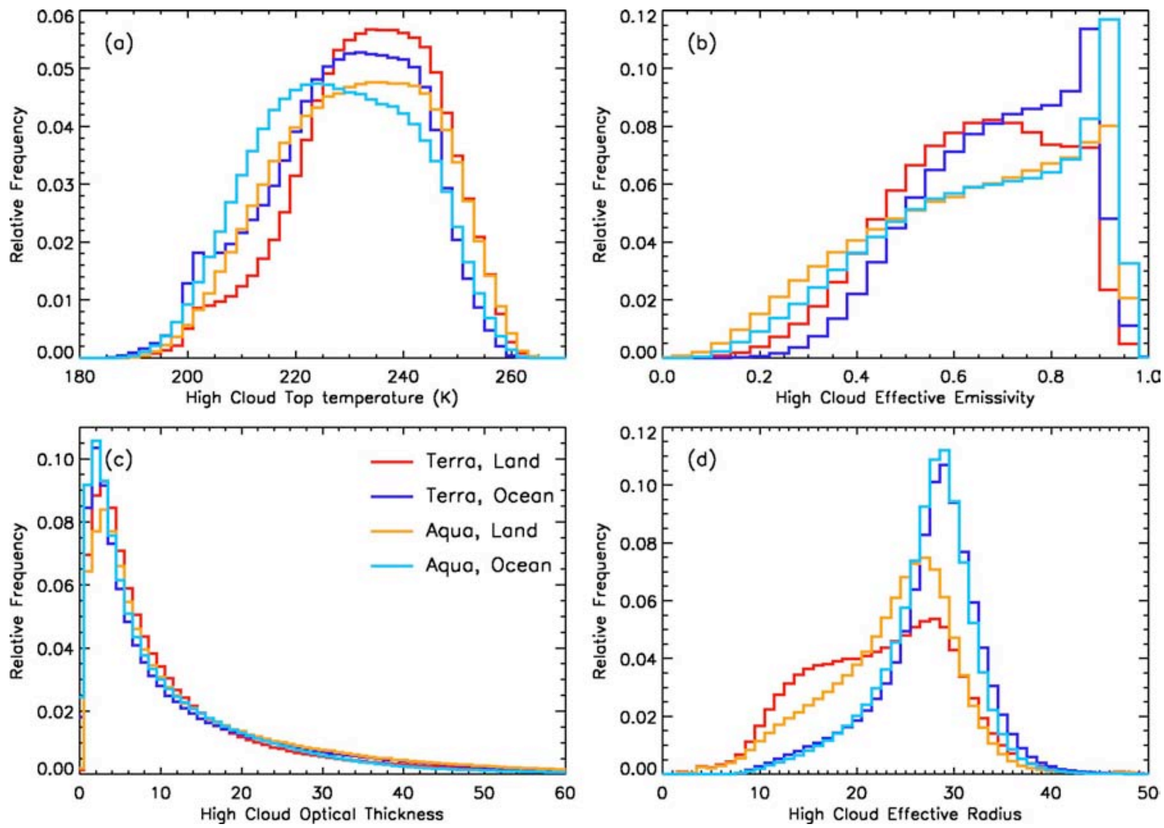

Figure 1. Frequency distributions of (a) cloud top temperature, (b) effective emissivity, (c) optical thickness, and (d) effective particle size for high clouds over ocean and land in the tropics (30°S–30°N) from Terra and Aqua.

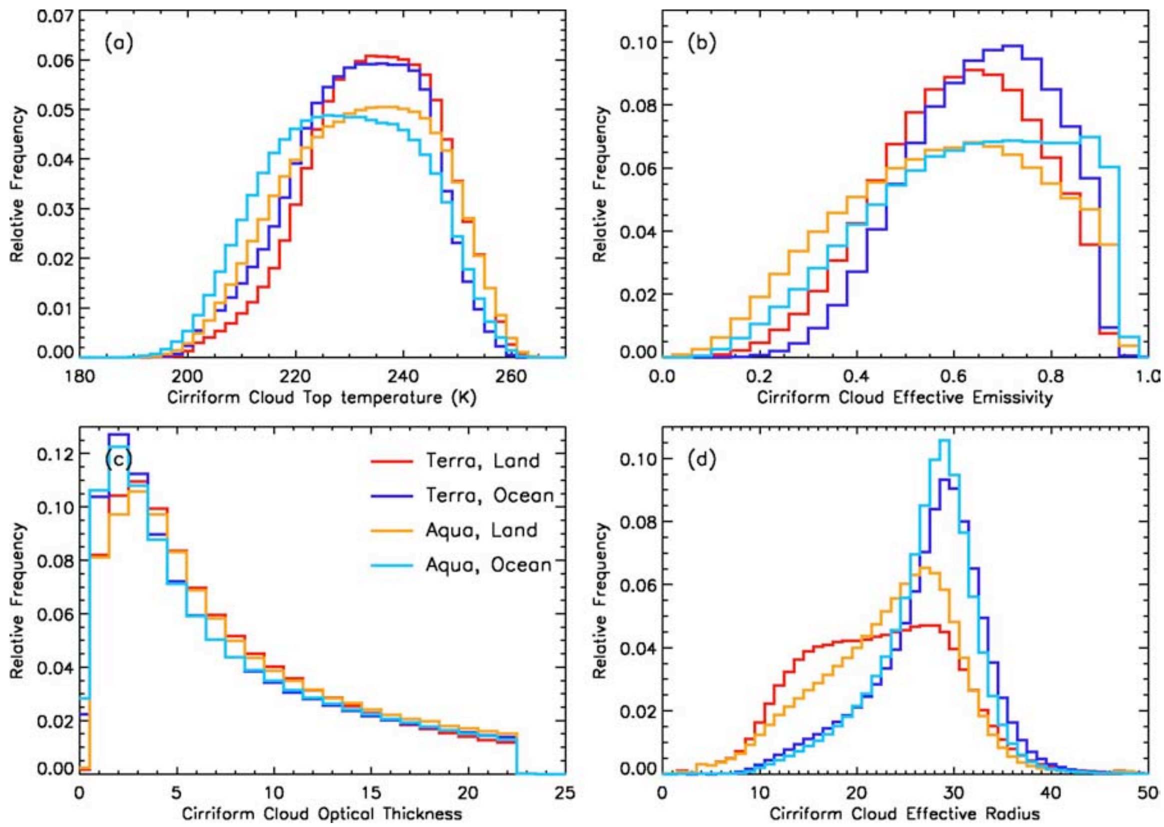

Figure 2. Same as Figure 1, but for cirriform clouds.

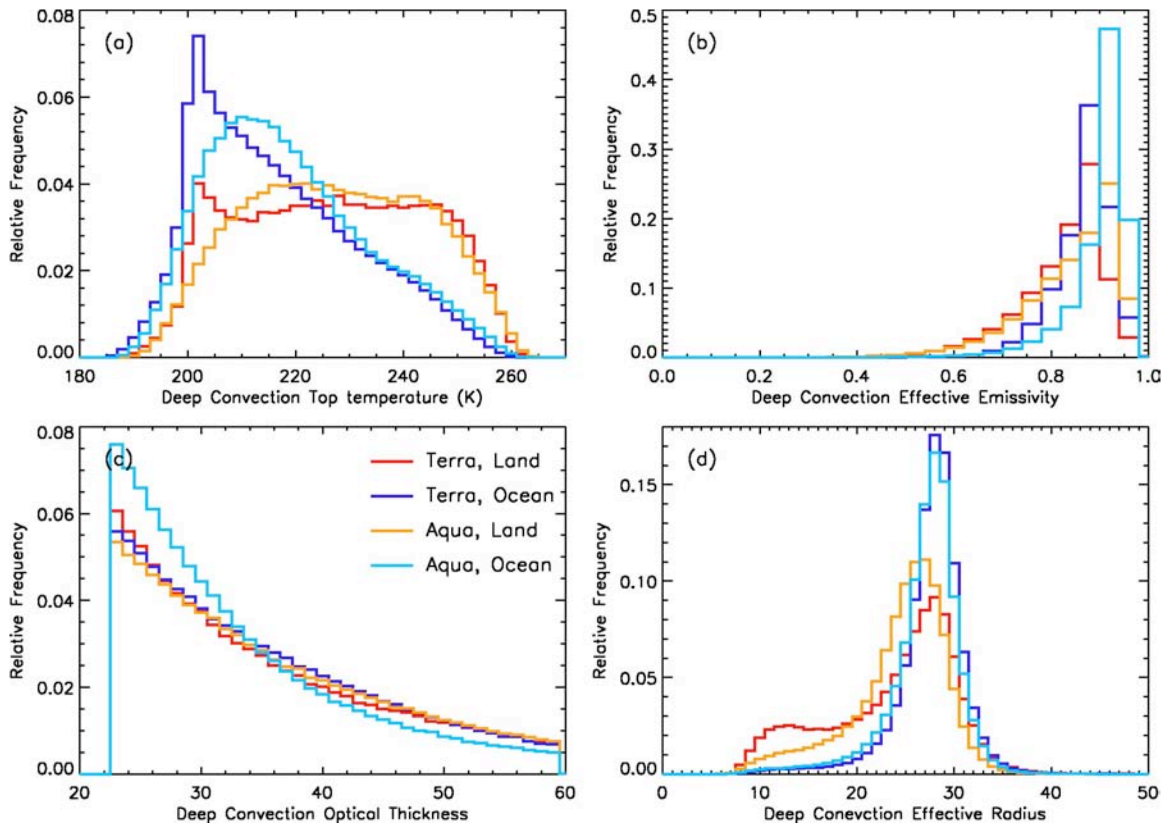

Figure 3. Same as Figure 1, but for deep convective clouds.

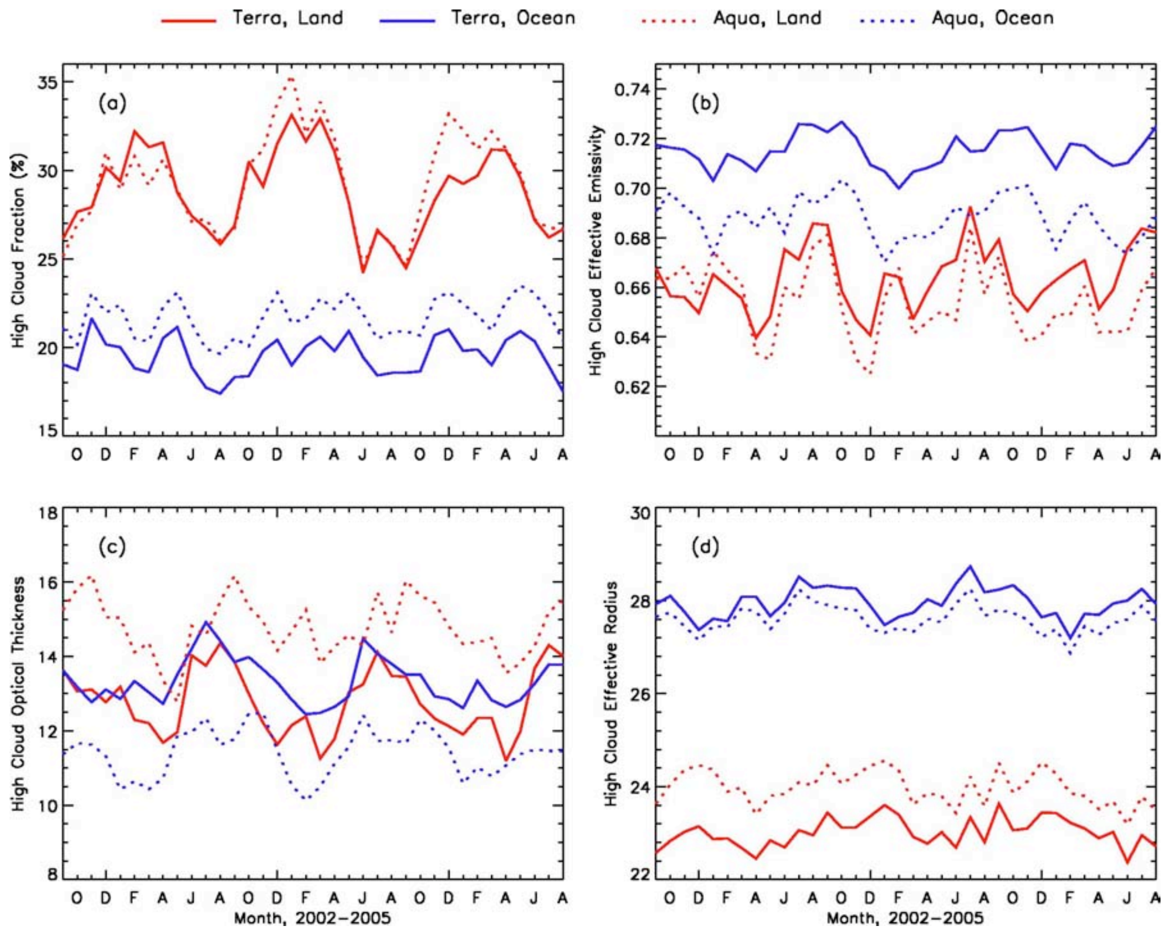

Figure 4. Monthly variations of (a) high cloud fraction, (b) effective emissivity, (c) optical thickness, and (d) effective particle size averaged over the tropics (30°S–30°N) from Terra and Aqua.

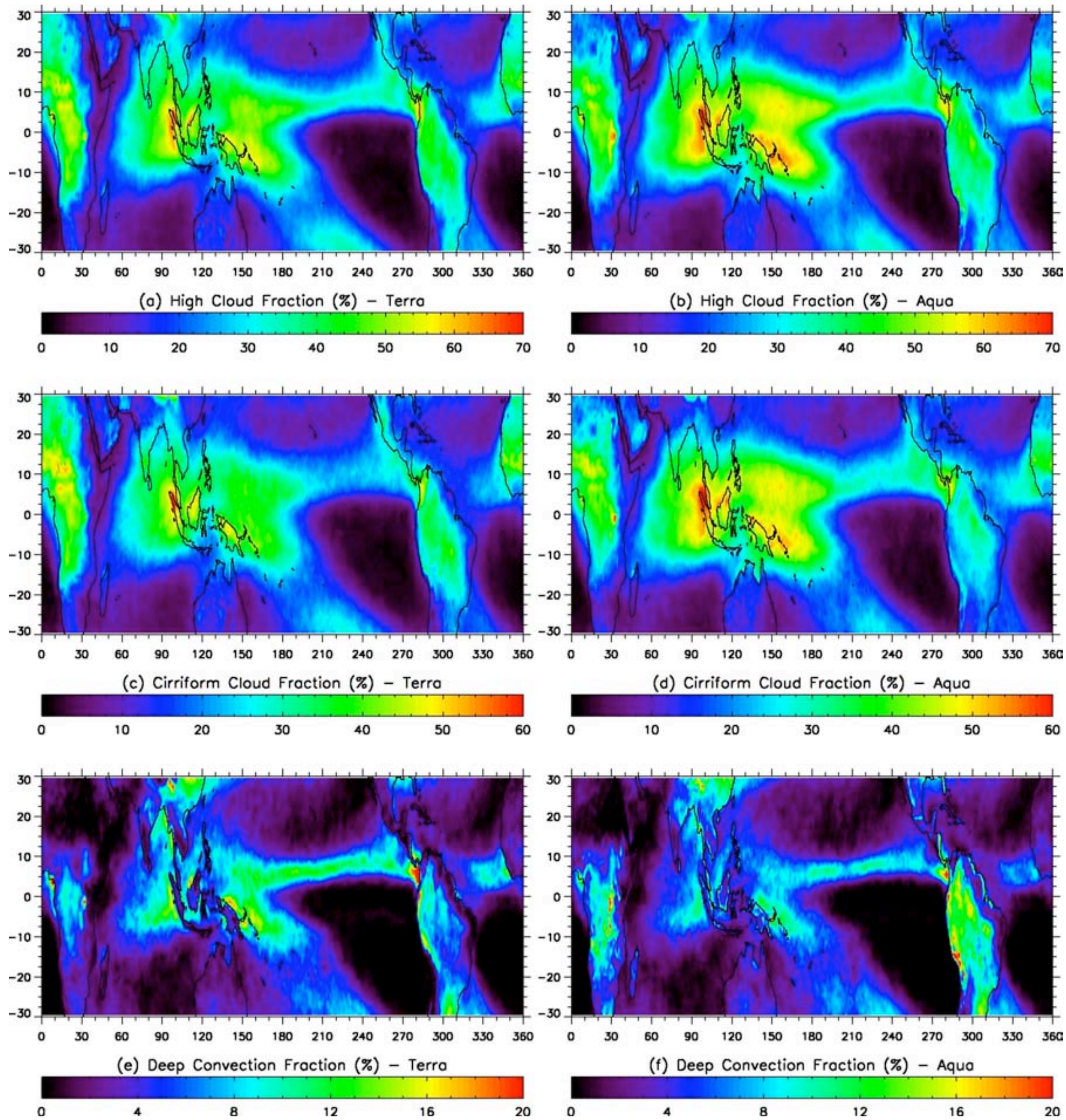

Figure 5. Geographical distributions of the three-year mean fractions of high cloud and cirriform cloud and deep convective cloud from Terra (left panels) and Aqua (right panels) over the tropics (30°S−30°N).

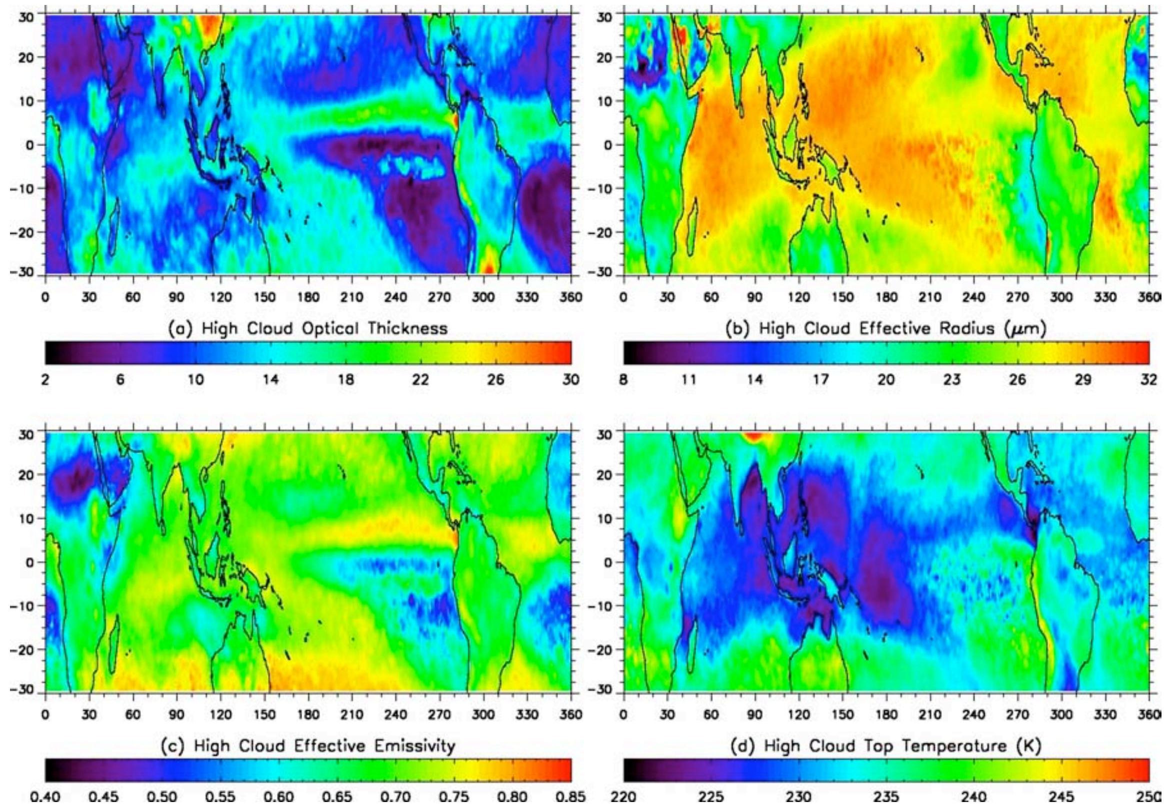

Figure 6. The geographical distributions of three-year means of (a) high cloud optical thickness, (b) effective particle size, (c) effective emissivity, and (d) top temperature from Terra over the tropics (30°S–30°N).

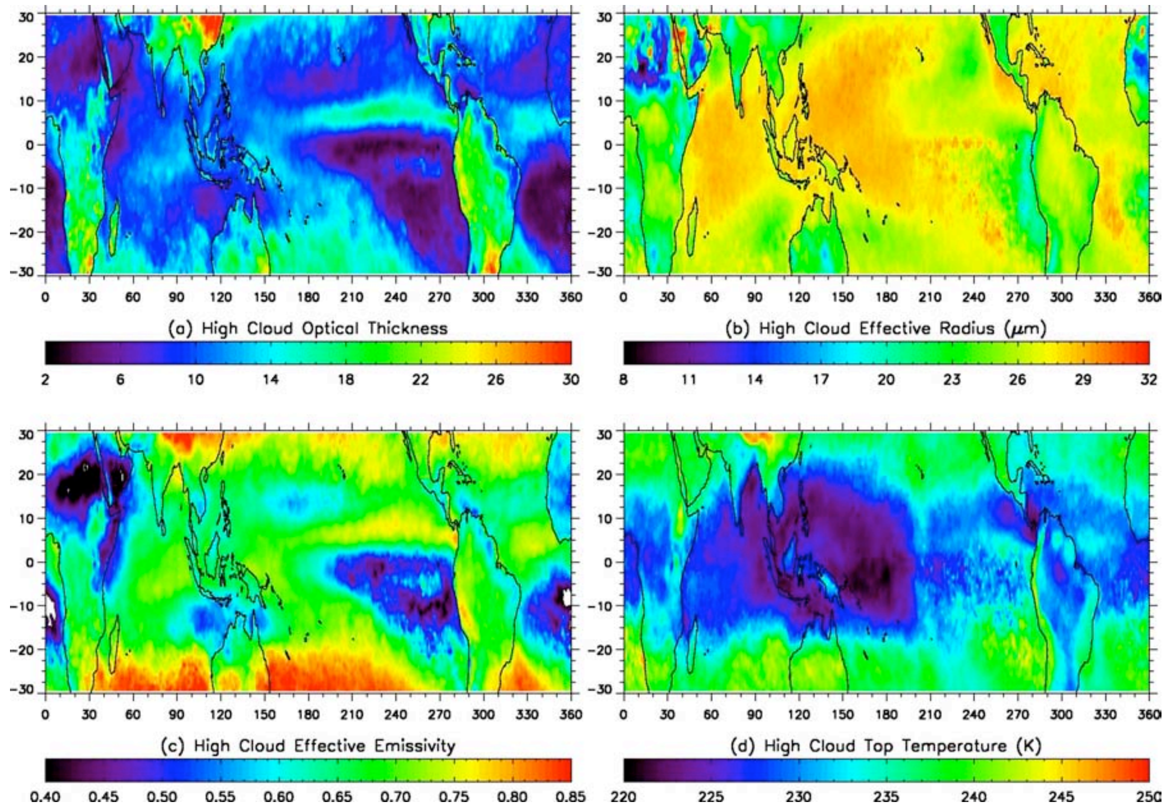

Figure 7. Same as Figure 6, but for Aqua.

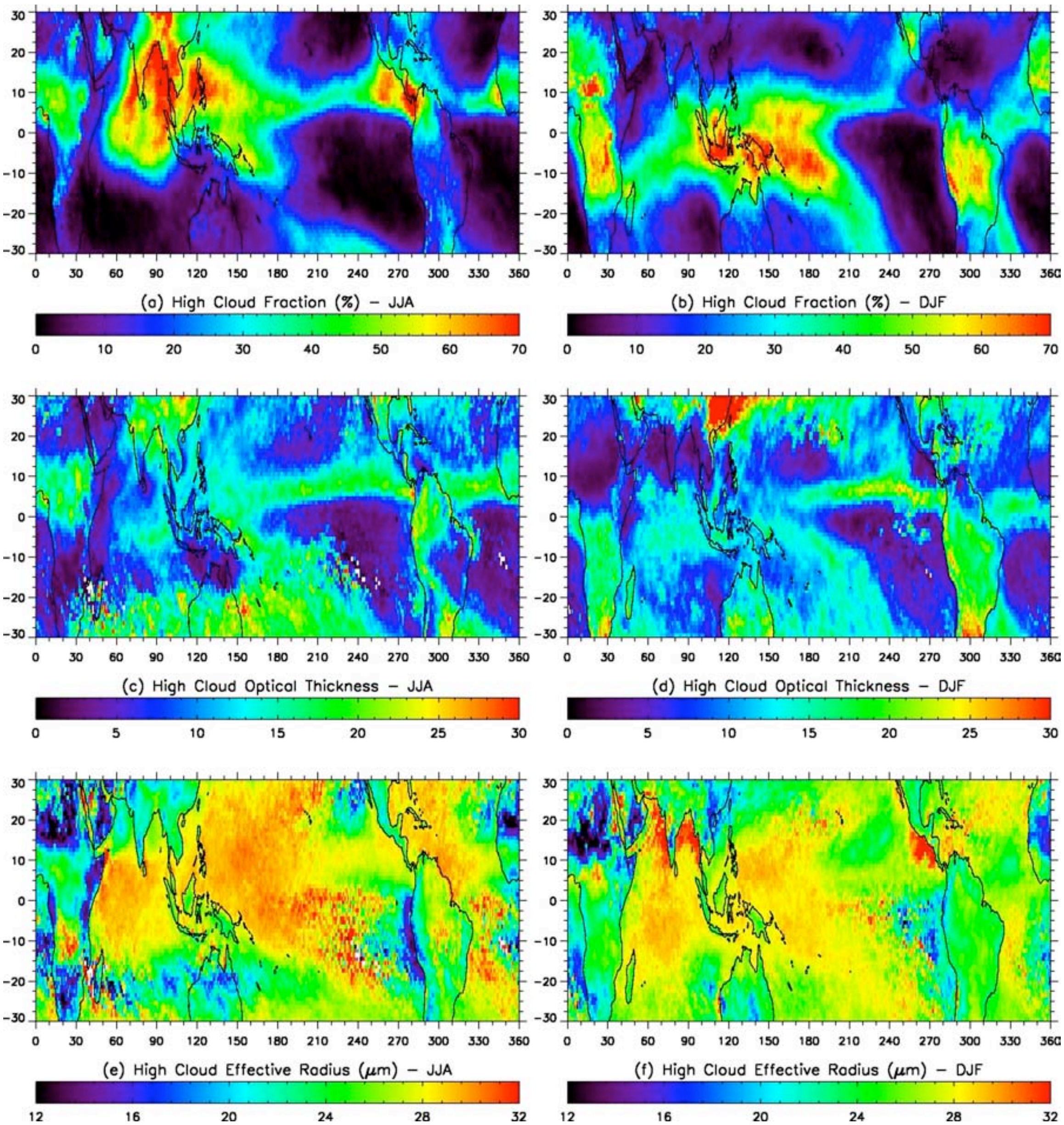

Figure 8. The seasonal distributions of high cloud fraction, optical thickness, and effective particle size in the northern hemisphere summer (left panels) and winter (right panels) seasons derived from the three-year Terra and Aqua data over the tropics (30°S–30°N).

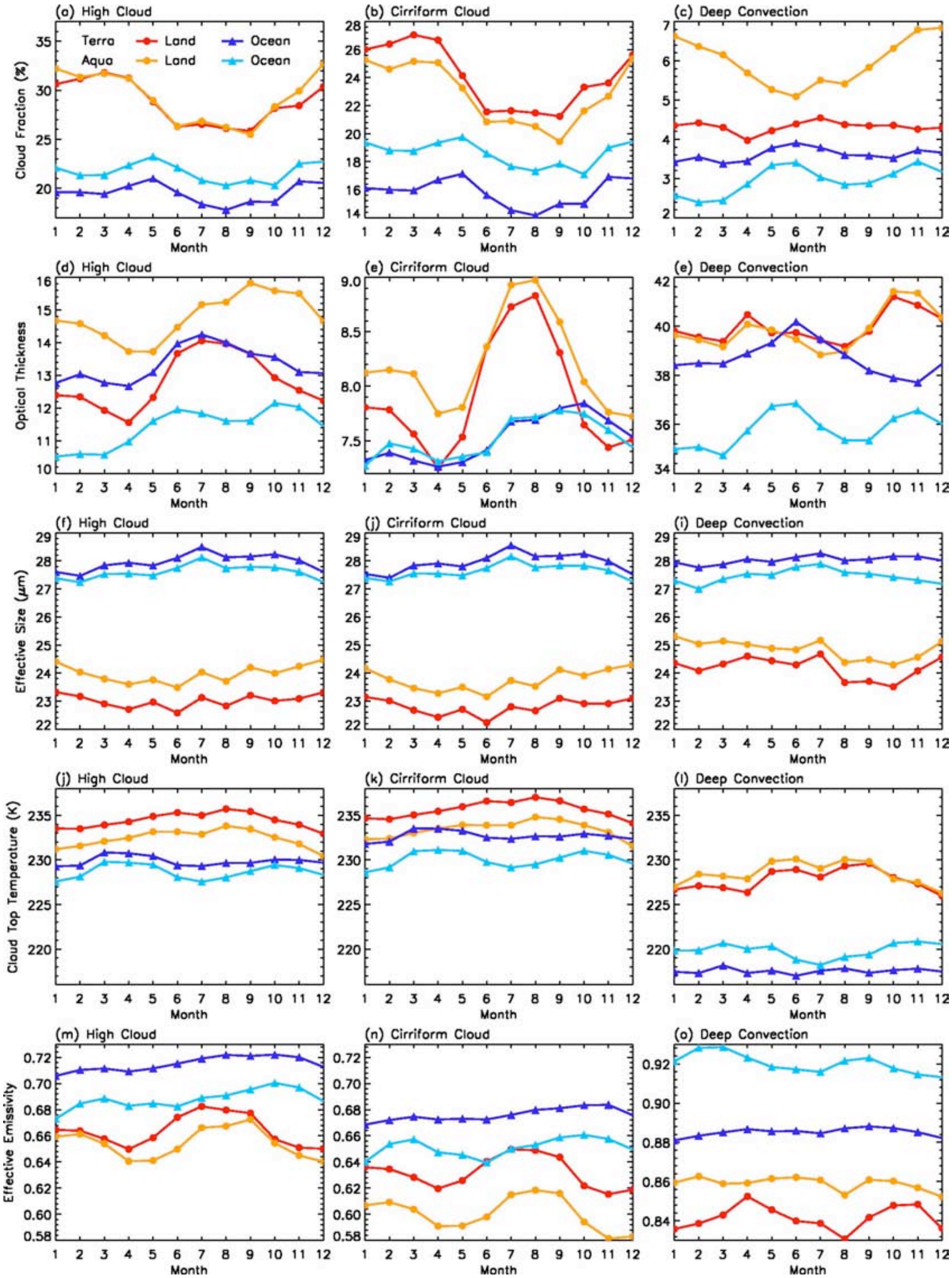

Figure 9. Seasonal variation of cloud fraction, optical thickness, effective size, cloud top temperature, and effective emissivity of high cloud and cirriform and deep convective clouds from the Terra and Aqua over the tropical land and ocean (30°S–30°N).

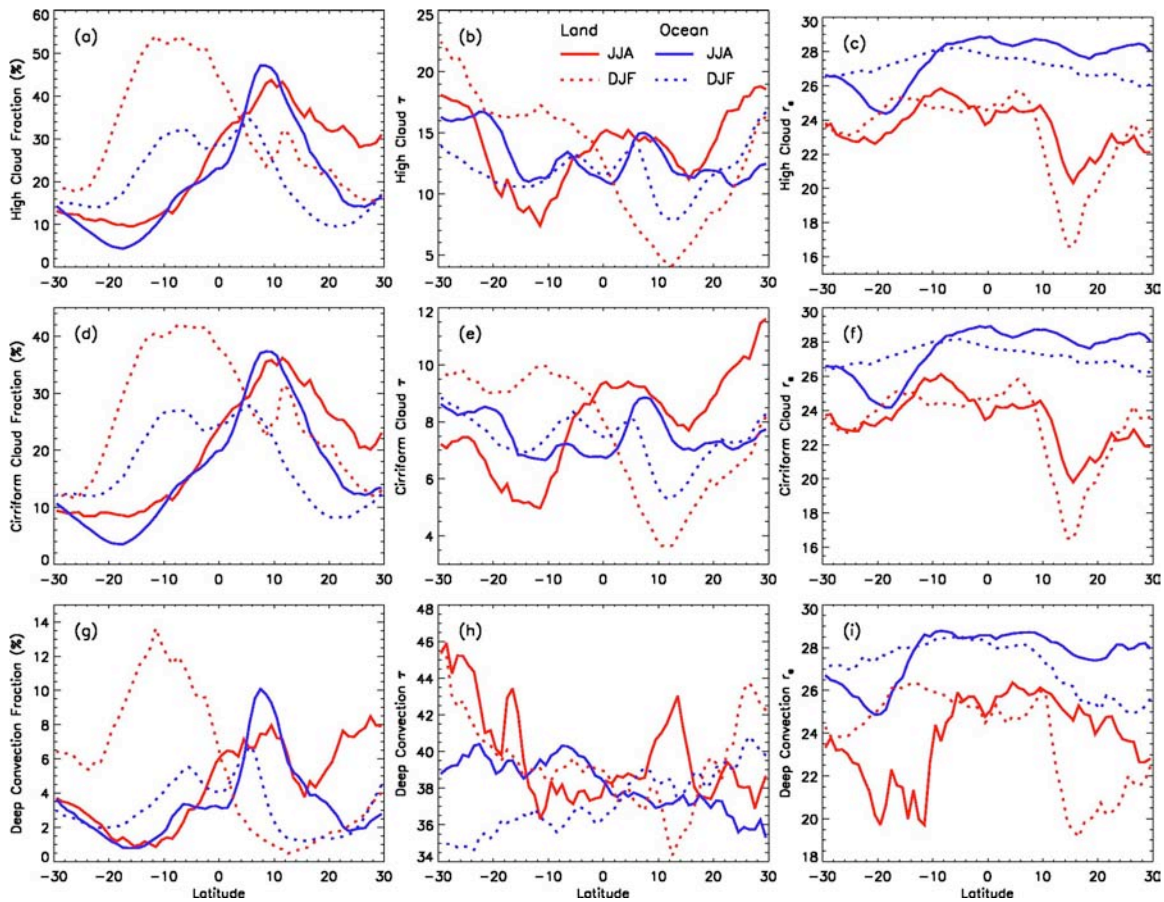

Figure 10. The zonal means cloud properties of tropical high cloud and cirriform and deep convective clouds over land and ocean along latitudes in summer (JJA) and winter (DJF).